KRUSTY Integral Experiments, Modeling & Stability

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Jeffery Goettee, James Jurney, Robert Kimpland & Steven Klein

Los Alamos National Laboratory

Advanced Nuclear Technology Group (NEN-2)

Manufacturing Science & Engineering (MET-2)

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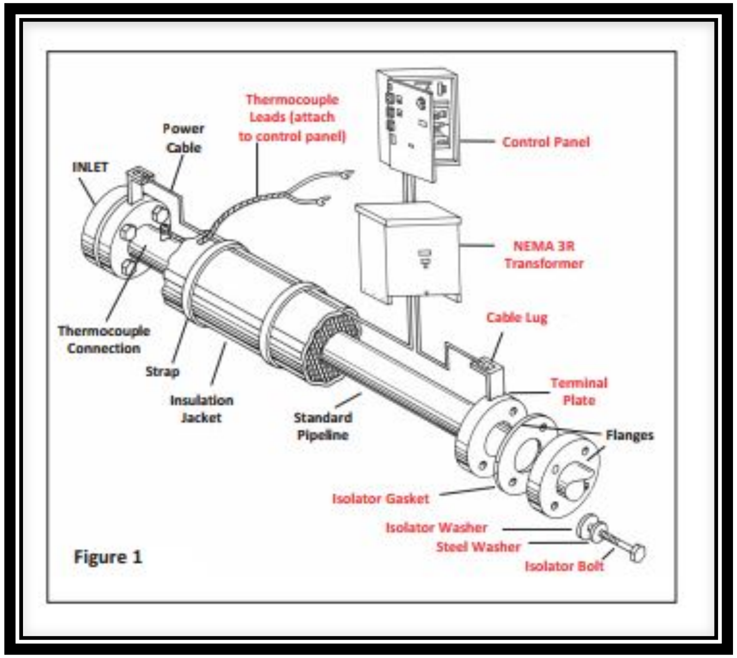
Purpose

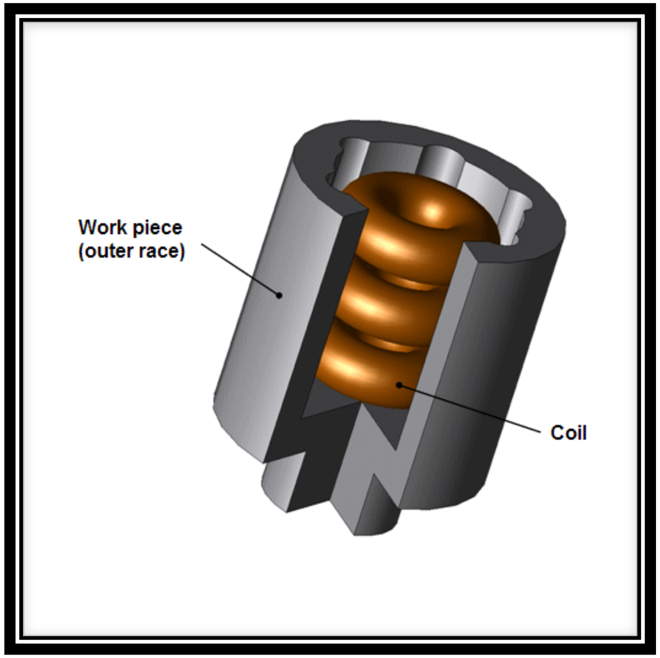
- **Refine predicted performance through integral experiments focused on reducing uncertainties in parameters**
  - Reactivity coefficients and cross sections of fuel, BeO reflectors, vessels, and other components across operating temperature range
  - Temperature and mechanical response of components as function of core temperature
  - Thermal reactivity feedback of core, reflector and cooling mechanisms
  - Sensitivity of performance to physical parameters and configuration
  - Dynamics including start-up and off-normal events
- **Refine dynamic models as experimental data becomes available**
  - Verify and ultimately validate predicted steady-state operation
  - Estimate system response to dynamic events such as start-up and off-normal events
  - Demonstrate theoretical stability of the system

Experimental Campaign – Core Heating

- **Core heating (impedance or inductive)**
  - Impedance method supplies electric current directly to uranium core; would be mounted in hollow center of the core; through vacuum vessel electrodes; power controller supply for required seven (7) kilowatts to heat to 800°C (1472°F)
  - Inductance heating through coupled energy through hollow center; efficiencies require eleven (11) kilowatts to heat.

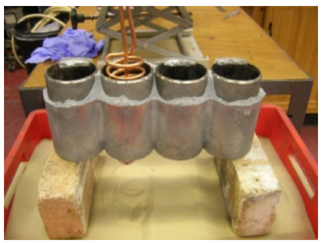


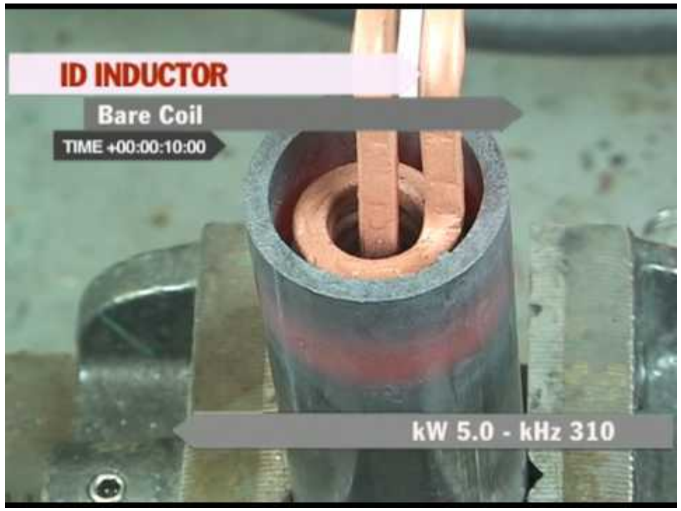
Impedance Concept

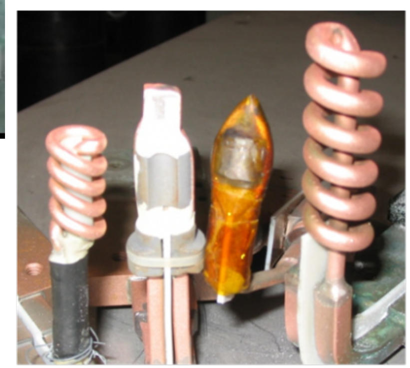


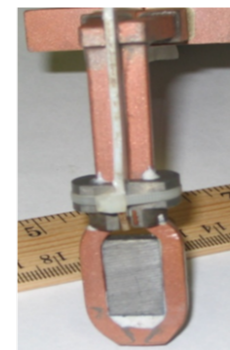
Inductance Concept

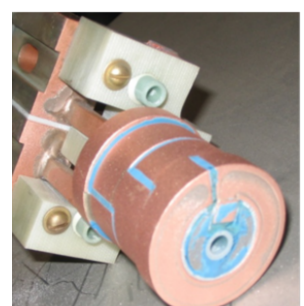
Core Heating – Examples

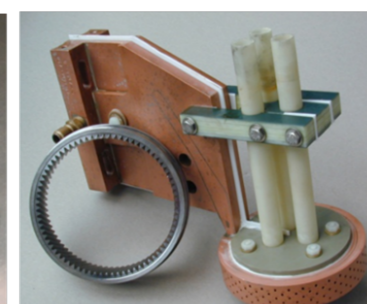






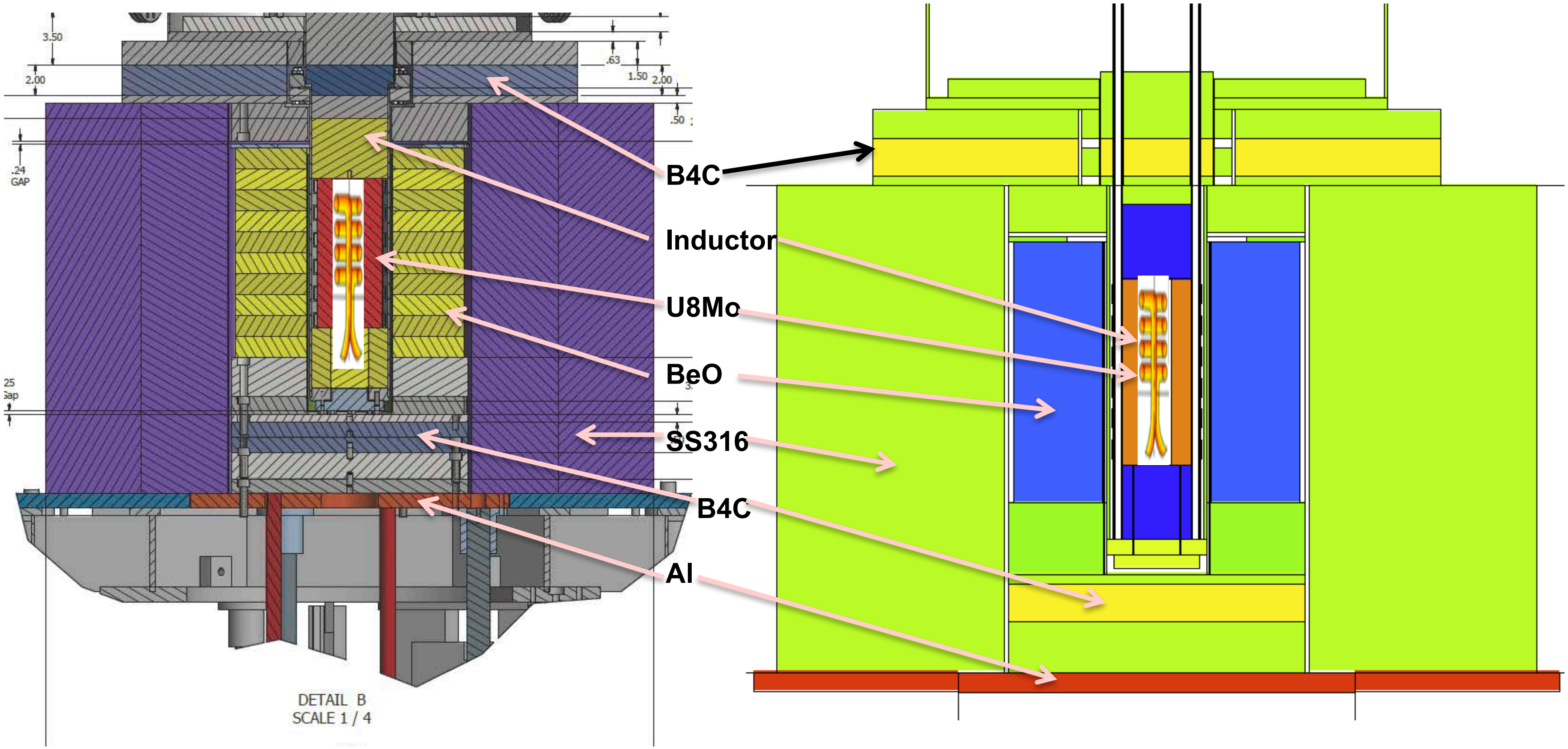






- **Many configurations possible**
- **Support of manufacturing and experimental operations**
- **Handling of Plutonium, Uranium and similar materials**
- **Dynamic heating profiles**

Zero-Power Critical Experimental Concept



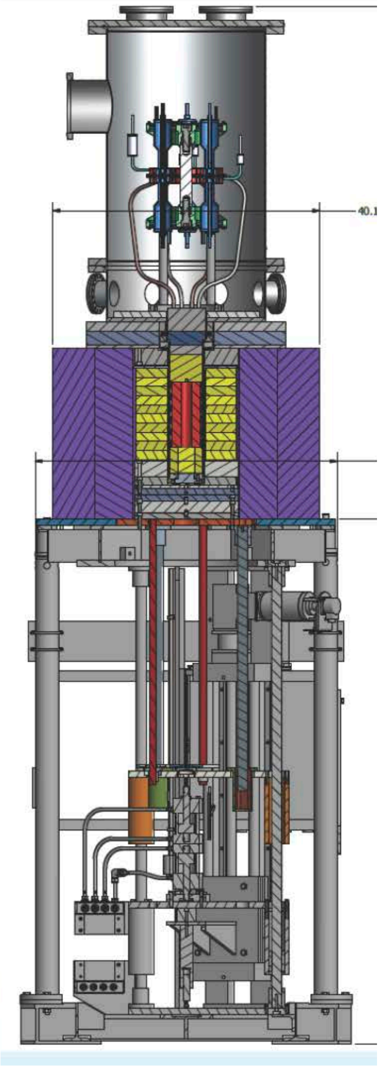
- Establish Zero Power throughout operating temperature range (20°C - 800°C)
- No vessel, heat pipes or other structures required
- Potential for smaller scale experiments involving only BeO

Inductance option shown

Critical Experiments – Full Configuration

Mounted on Comet Critical Assembly

- Repeat zero-power experiments with sub-critical heating to examine system performance
- Perform selected off-normal events
- Repeat temperature profile at power

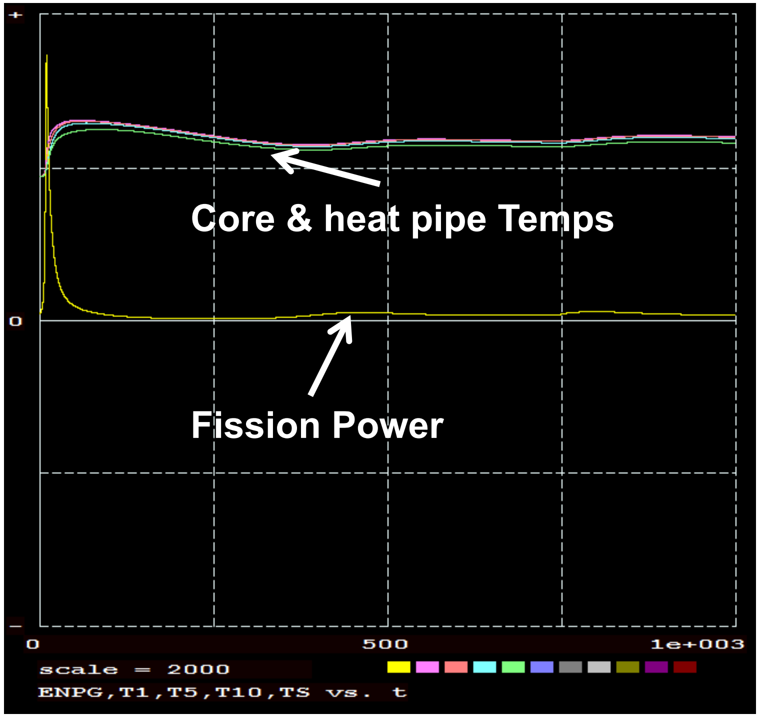


Critical Experiments – Safety, Security & Operational Issues

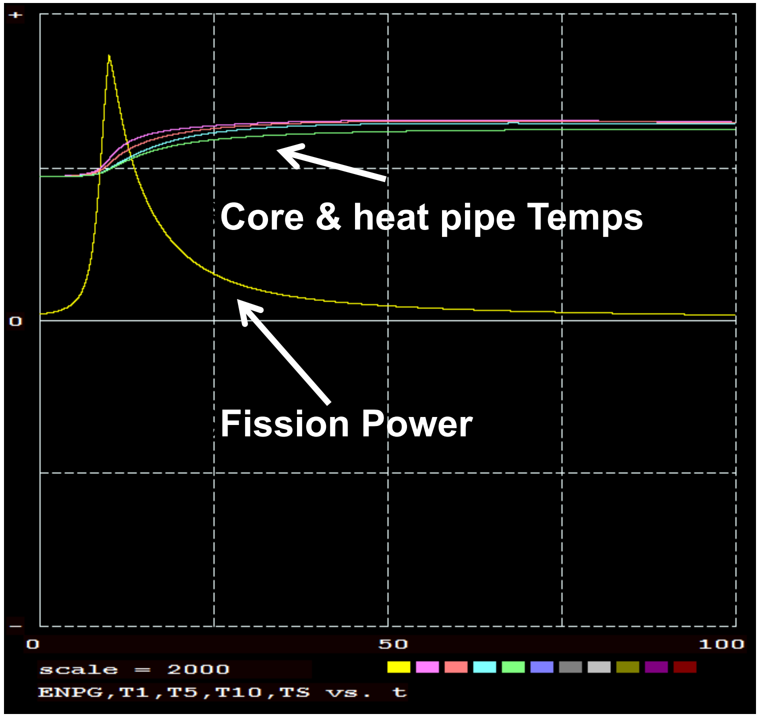
- **72 hours continuous operation**
- **Excess reactivity (~$3.00 versus current $0.80 limit)**
- **Operations with vacuum chamber**
  - Determination of preoperational checks
  - Monitoring requirements
  - Actions arising from breach
- **Temperature of operation**
  - Monitoring requirements
  - Limits
- **Handling and disposition of fission gasses**
  - Exhaust or trap? (Environmental Impact Statement determination)
  - If exhaust determine operational mode of HVAC system
- **Effects of reflector cooling, material sweep, and potential HEPA filtration**

Dynamic System Simulation (DSS)

- Coupled nuclear kinetics and thermo-hydraulics with expected reactivity feedback
- Startup, transition to steady-state and off normal events modeled
- Current model uses generic heat transfer mechanism

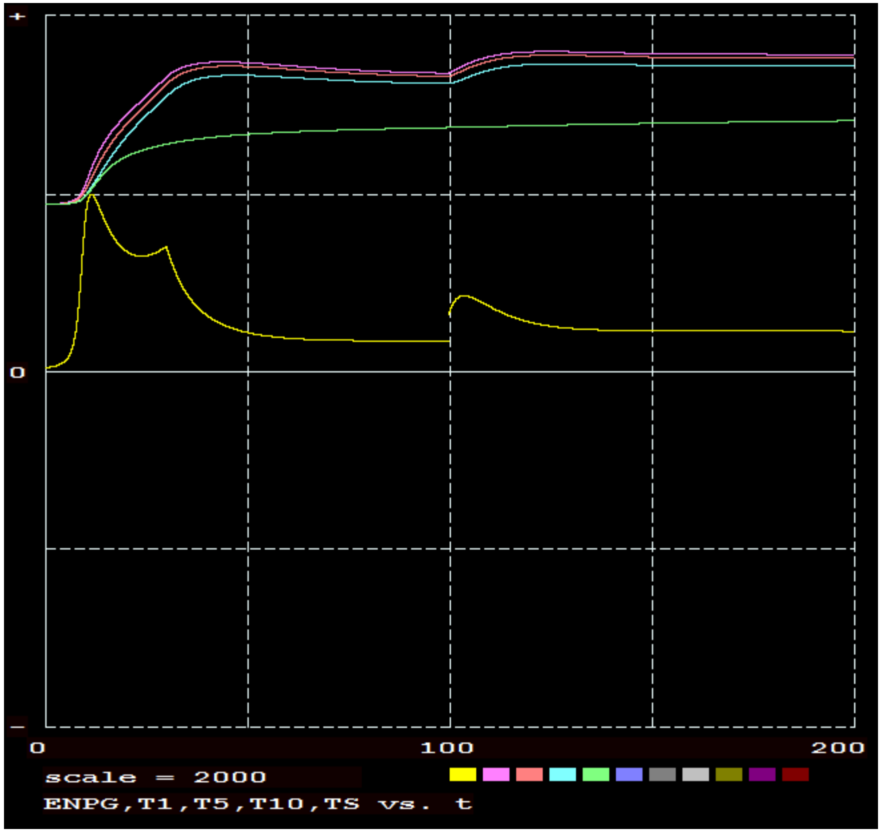


$1.00 insertion

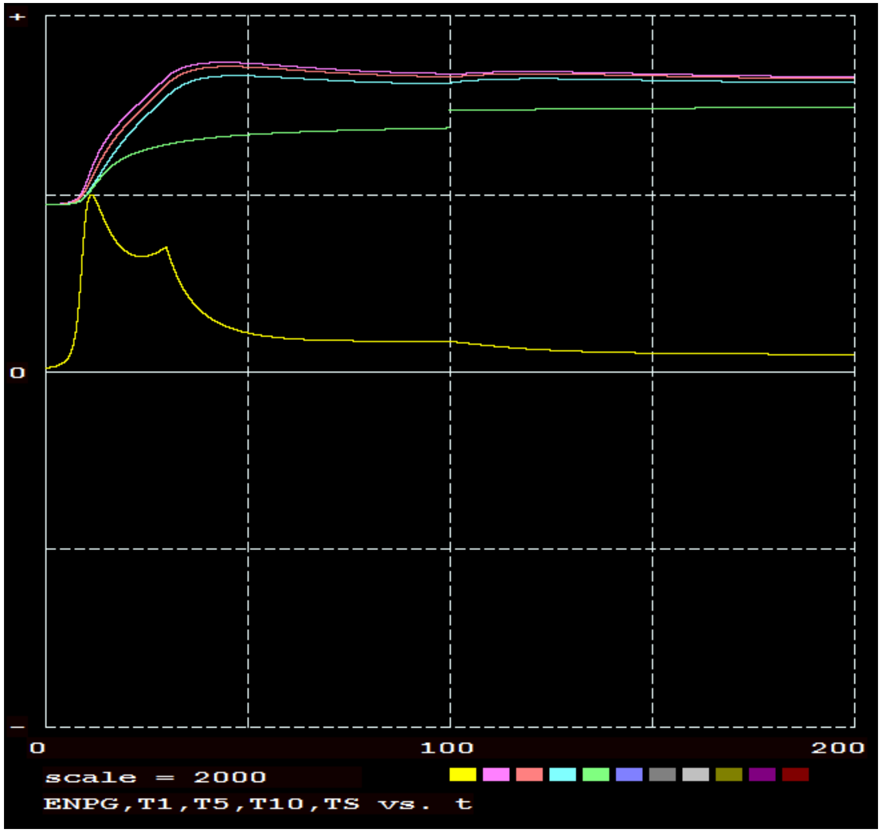


$1.00 insertion (Detail)

DSS with Off-Normal Event Response

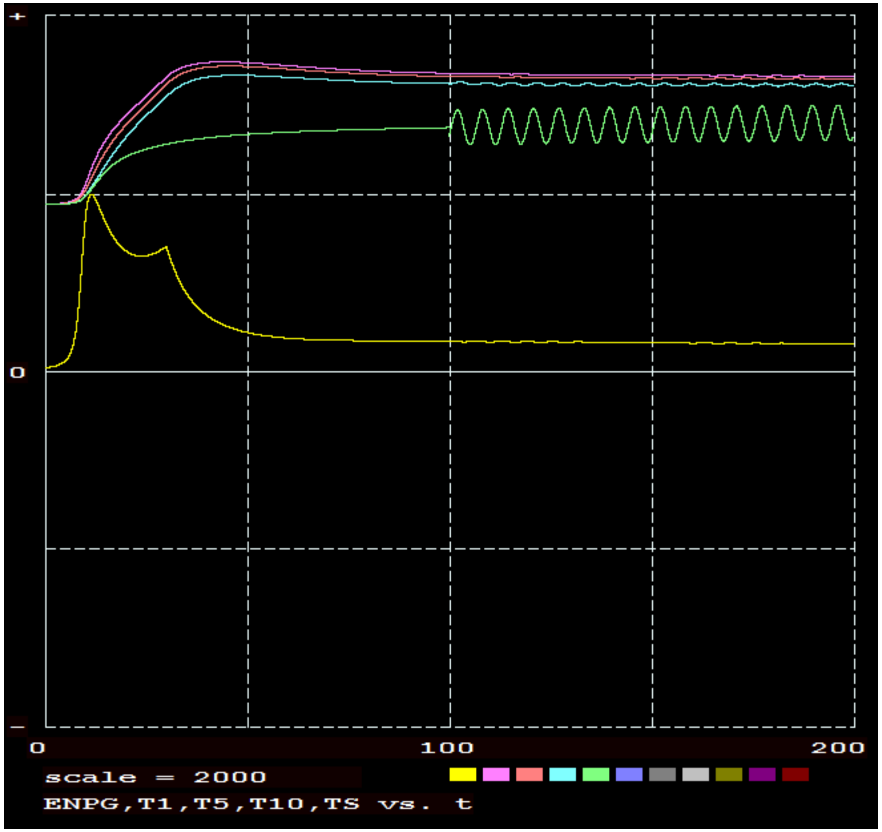


$0.50 Reactivity Step

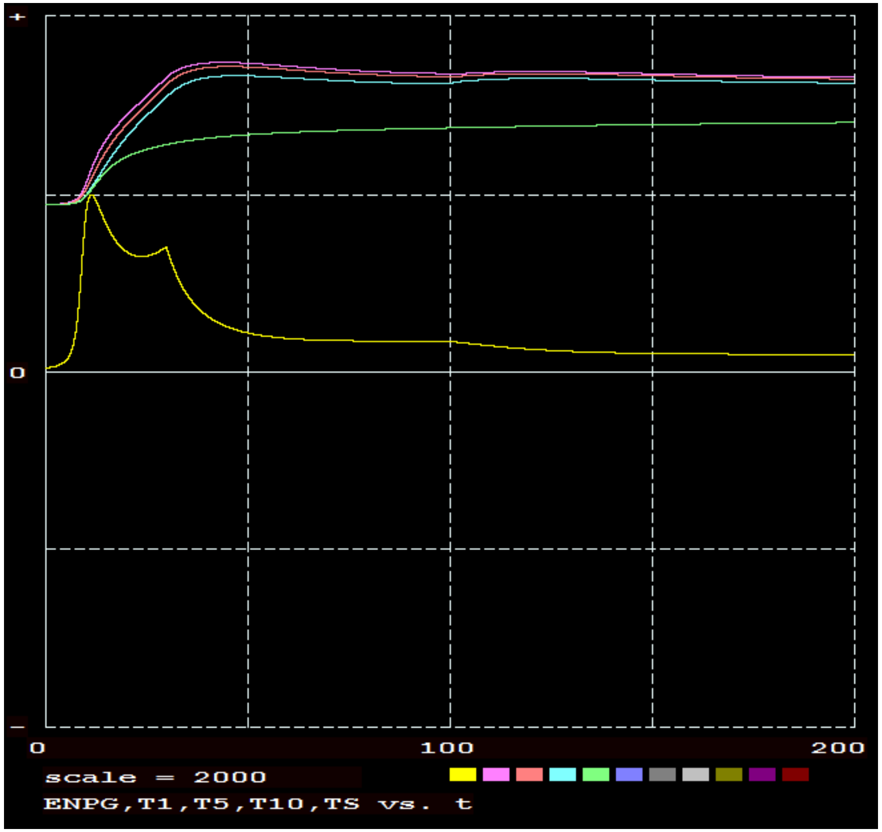


100°C Saturation Temperature Step

DSS Off-Normal II

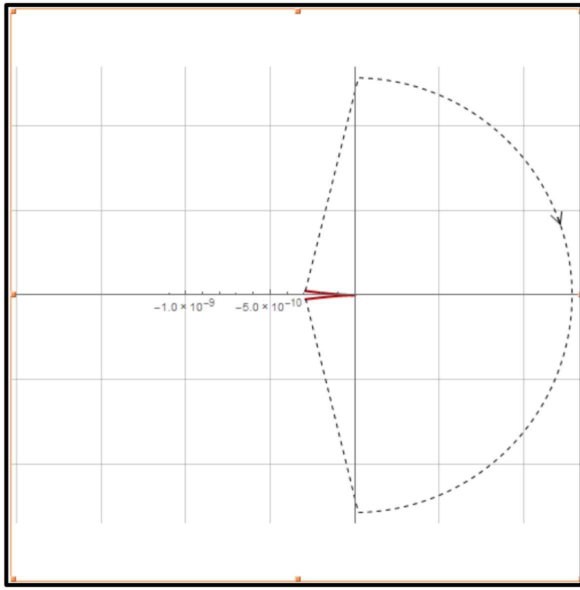


Temperature Oscillation

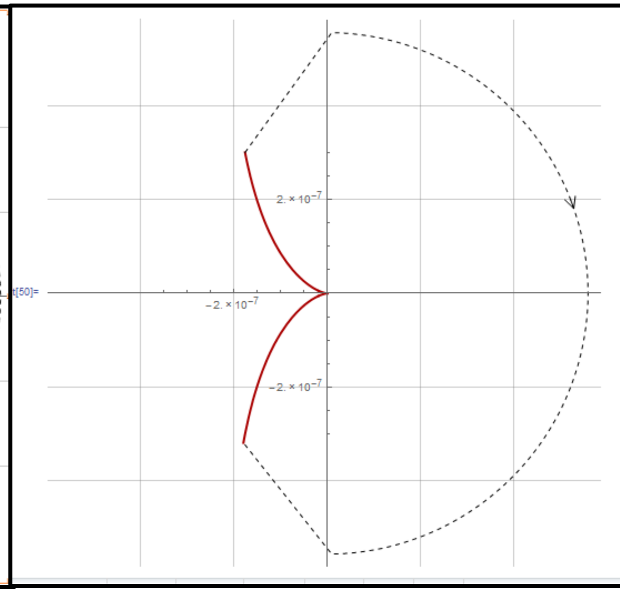


Loss of Heat Pipe Function

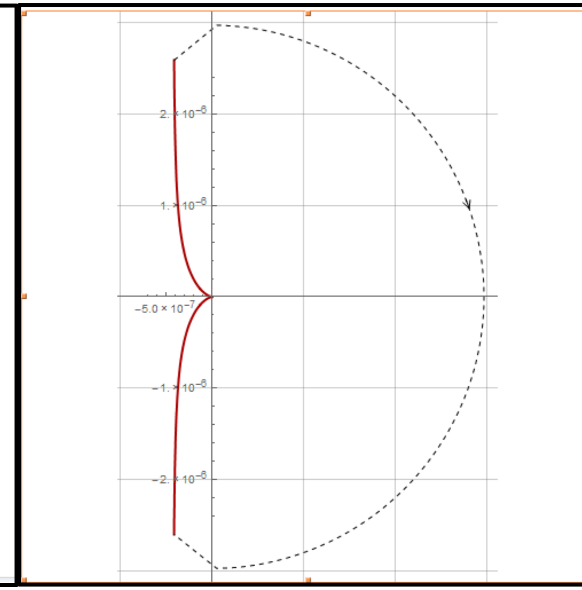
Stability Model – Nyquist Plots



$0.25



$0.50

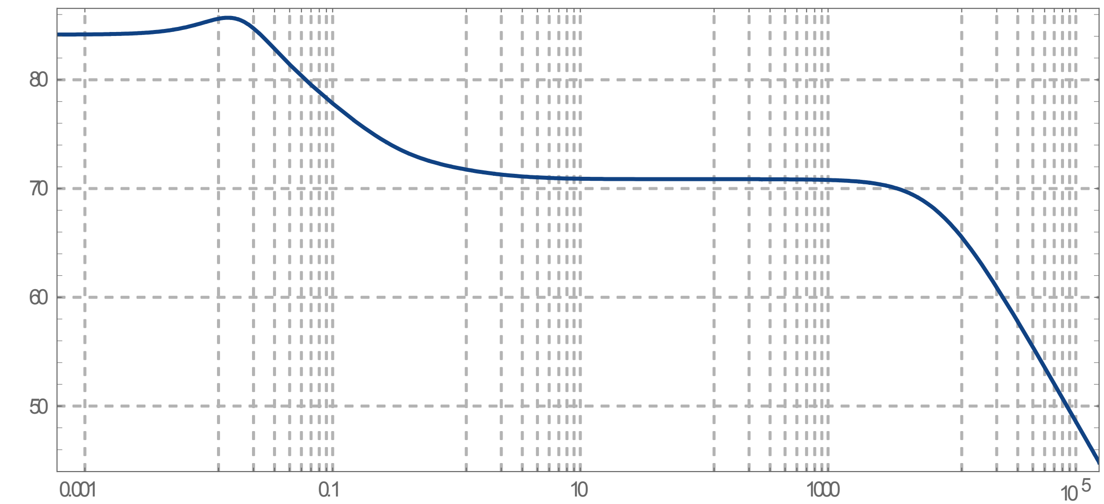


$1.00

- Higher power results in wider stability margin
- No positive zeros in Open Loop Transfer Function
- Does not encircle -1

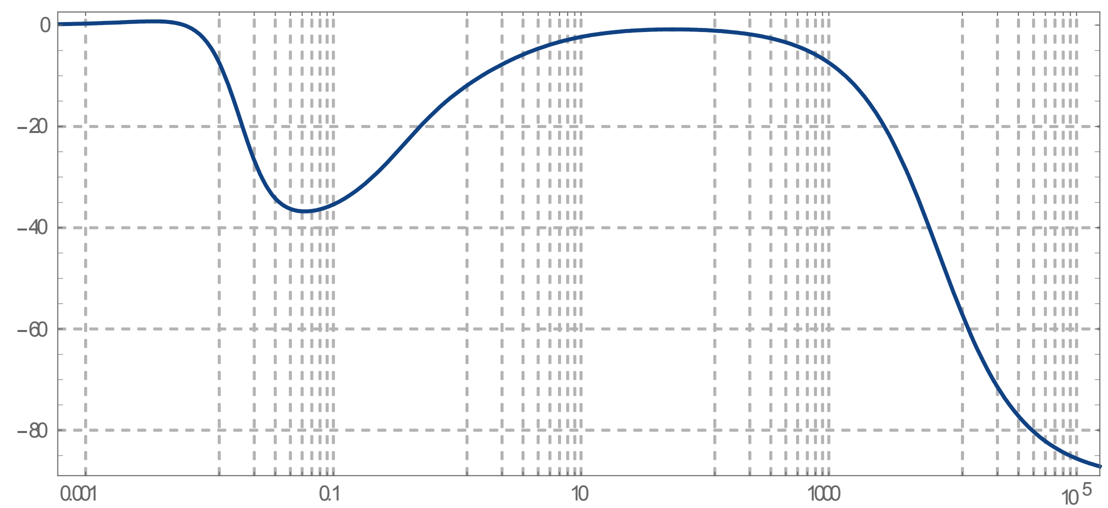
Model is unconditional stable in the linear approximation

Stability Model – Bode Plots



Amplitude – Top
Frequency – Bottom

- Response is benign
- No discontinuities
- Consistent with Nyquist conclusions



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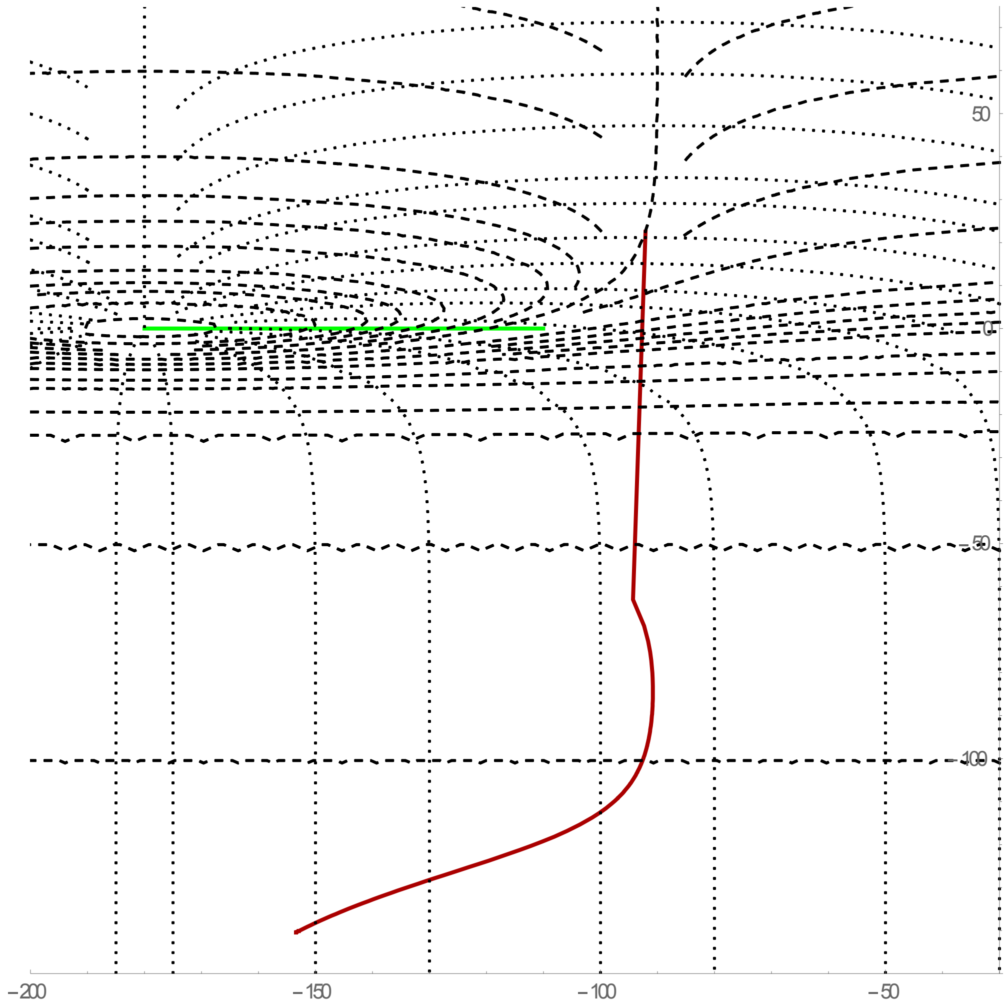
Stability Model – Nichols Plot

- Shows wide stability margin (~75°)
- Result consistent with Nyquist



Analysis of Transfer Function Stability

- **Bethe Criteria – No infinite resonance in Bode Plots**
- **Nyquist Criteria – Number of clockwise encirclements of 1- plus the number of right hand plane poles is zero (transfer function has not positive poles)**
- **Nichols Criteria – One sheeted full Nichols plot of the transfer function does not intersect the point (-180, 0 db)**

These are necessary and sufficient to establish stability of the model in the linear approximation

Bethe criteria is necessary for non-linear system stability

Conclusions and Recommendations

- Proposed experimental campaign, including zero power critical over full temperature range will minimize uncertainties in important parameters
- Experiments at power will demonstrate system functionality and operability
- Dynamic System model establishes basis for operation and system stability; however, generic heat transfer mechanism used in current model; improvements to be made once experimental data available
- Experimental results may be used to refine model to provide an operational tool